SILVA BALCANICA

Silva Balcanica 21(1): 29–40 (2020)
doi: 10.3897/silvabalcanica.21.e54425

REVIEW ARTICLE

Application of Nelder wheel experimental design in forestry research

Tatiana Stankova

Forest Research Institute, Bulgarian Academy of Sciences, 132 St. Kliment Ohridski Blvd., 1756 Sofia, Bulgaria

Corresponding author: Tatiana Stankova (tatianastankova@yahoo.com)

Academic editor: I. Markoff | Received 10 March 2020 | Accepted 12 April 2020 | Published 30 June 2020

Citation: Stankova T. (2020) Application of Nelder wheel experimental design in forestry research. Silva Balcanica 21(1): 29–40. https://doi.org/10.3897/silvabalcanica.21.e54425

Abstract

This article presents a concise review on the forestry research, which involves application of a Nelder wheel experimental design, a type of systematic design for spacing trials. Short presentation of the design is included, practical applications of various objectives and methodological approaches to data analysis are outlined and the pros and cons of the design are discussed.

Keywords

Spacing, systematic design, tree growth, competition, data analysis

Background

In 1962, the British statistician John Nelder introduced a family of systematic, circular experimental designs as an alternative to the replicated, full factorial spacing experiments, overcoming some of their space and plant material restrictions (Nelder, 1962). The Nelder 'wheel' design is a circular plot containing concentric circumferences radiating outward, with spokes connecting the centre with the furthest circumference and the trees planted at the intersections of spokes and circumferences (Figure 1). Nelder (1962) suggested four circular designs: Ia – with constant shape of the growing space and varying along the radii size; Ib – with constant size of the growing space and varying along the radii shape; Ic, Id – combining, in two differ-

Copyright *Tatiana Stankova*. This is an open access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

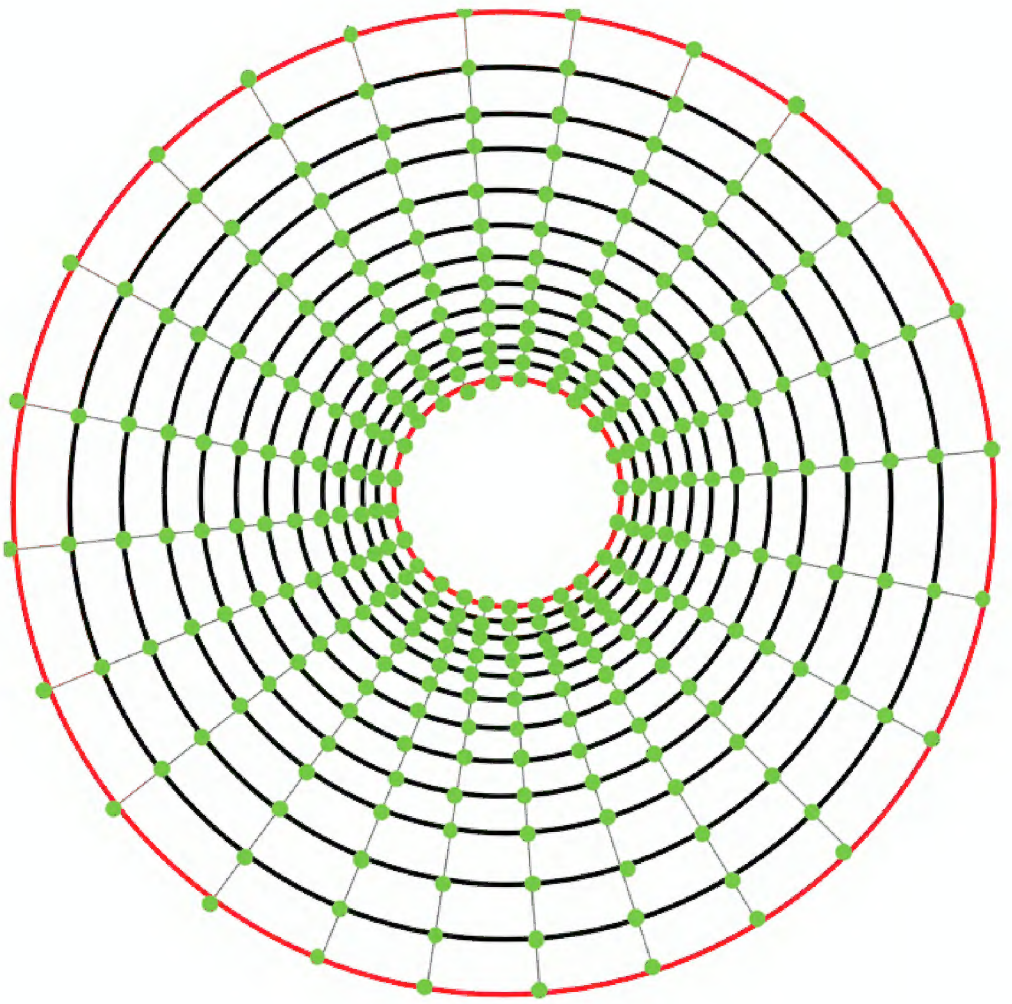

Figure 1. Schematic representation of a Nelder wheel (design Ia)

ent manners, constant and variable shape and size of the growing space. The Nelder wheel variant Ia was the one predominantly adapted in the spacing experiments with forest tree species. According to Namkoong (1965), all four versions may be made suitable to silvicultural experiments, but Nelder wheels Ia and Ib could be adapted for small family or genotypic plots of interest to tree breeders. Of these two, in Nelder design Ia the size of the growing space varies along the spokes and the genetic factor changes along the concentric circumferences of the wheel. In his work, Namkoong (1965) not only extended the pure spacing experiment to two-factor trial plot, but also substituted the calculus-based layout equations of Nelder by trigonometry-based equations. Nelder wheel design and modifications have been broadly applied in forestry research for different tree species, families and clones to study a range of tree attributes by employing various data analysis techniques.

Estimation of a Nelder wheel (design Ia)

The systematic spacing design Ia consists of a grid of points (each representing the position of a plant), which has the property that the area per plant changes in some consistent fashion over the different parts of the grid and locally the design is assumed to be approximately rectangular (Nelder, 1962; Figure 2). Following the trigonometry-based equations by Namkoong (1965), the plot parameters are eas-

ily computed, if the densest (S_1, m^2) and the widest (S_n, m^2) growing spaces, the number of the planting densities (n) and the shape of the growing space, given by the factor of rectangularity β (ratio of between-spoke to within-spoke distance), are specified. Namkoong (1965) suggested the implementation of the following sequence of formulae to design a wheel with the desired properties:

$$\log \alpha = \frac{\log S_n - \log S_1}{2n-2} \quad (1)$$

$$4 \tan \theta = \beta(\alpha - \alpha^{-1}) \quad (2)$$

$$r_0 = \sqrt{\frac{4S_1}{\tan\left(\frac{\theta}{2}\right)} f(\alpha)} \quad (3),$$

$$f(\alpha) = a^2[(1+\alpha)^2 - (1+\alpha^{-1})^2] \quad (4)$$

$$r_i = r_0 \alpha^i \quad (5)$$

$$S_i = \frac{1}{4} \tan\left(\frac{\theta}{2}\right) \left[r_0^2 \alpha^{2i} f(\alpha)\right] \quad (6),$$

where θ is the angle between the adjacent spokes, α is the rate of change of the growing space, r_0 is the radius of the innermost circle, r_i is the radius of the i-th circle and S_i is the growing space corresponding to the i-th circle. The innermost and the outermost circles of radii r_0 and r_{n+1} respectively, are border circles (i.e. there are n+2 planting spots on a spoke).

Design applications in the forest studies

Since Nelder wheel design was developed as a systematic alternative to the randomised factorial spacing trials, the primary direction of its application was to study quantitative and qualitative parameters of trees in relation to density at different ages. Plant variables commonly studied are those related to growth and productivity: % survived plants, stem diameter (basal and breast-height), mid-stem girth, total height, basal area, stem volume, total and fractional biomass, leaf area (Decourt, Lemoine,. 1974; Delwaulle, 1979; Panestsos, 1980; Mark, 1983; Krinard, 1985; Reukema, Smith, 1987; Wurtz, 1995; Imada et al., 1997; Kerr, 2003; Aphalo, Rikala, 2006; Kirongo et al., 2012; Newton, 2015; Matos et al., 2015; Erkan, Aydin, 2016). Certain physiological parameters of growth, such as plant water potential, shoot photosynthetic potential, stomatal conductance and needle chemistry (Giordano, Hibbs, 1993; Doran et al., 2001), are addressed in some investigations, while other studies examine tree form and stem quality variables: height to the crown base, crown length, diameter and volume, height-diameter ratio, live crown ratio, stem and crown form, branchiness and epicormic branching, branch diameter, crown diameter to stem diameter ratio, internode length, relative bark thickness, wood

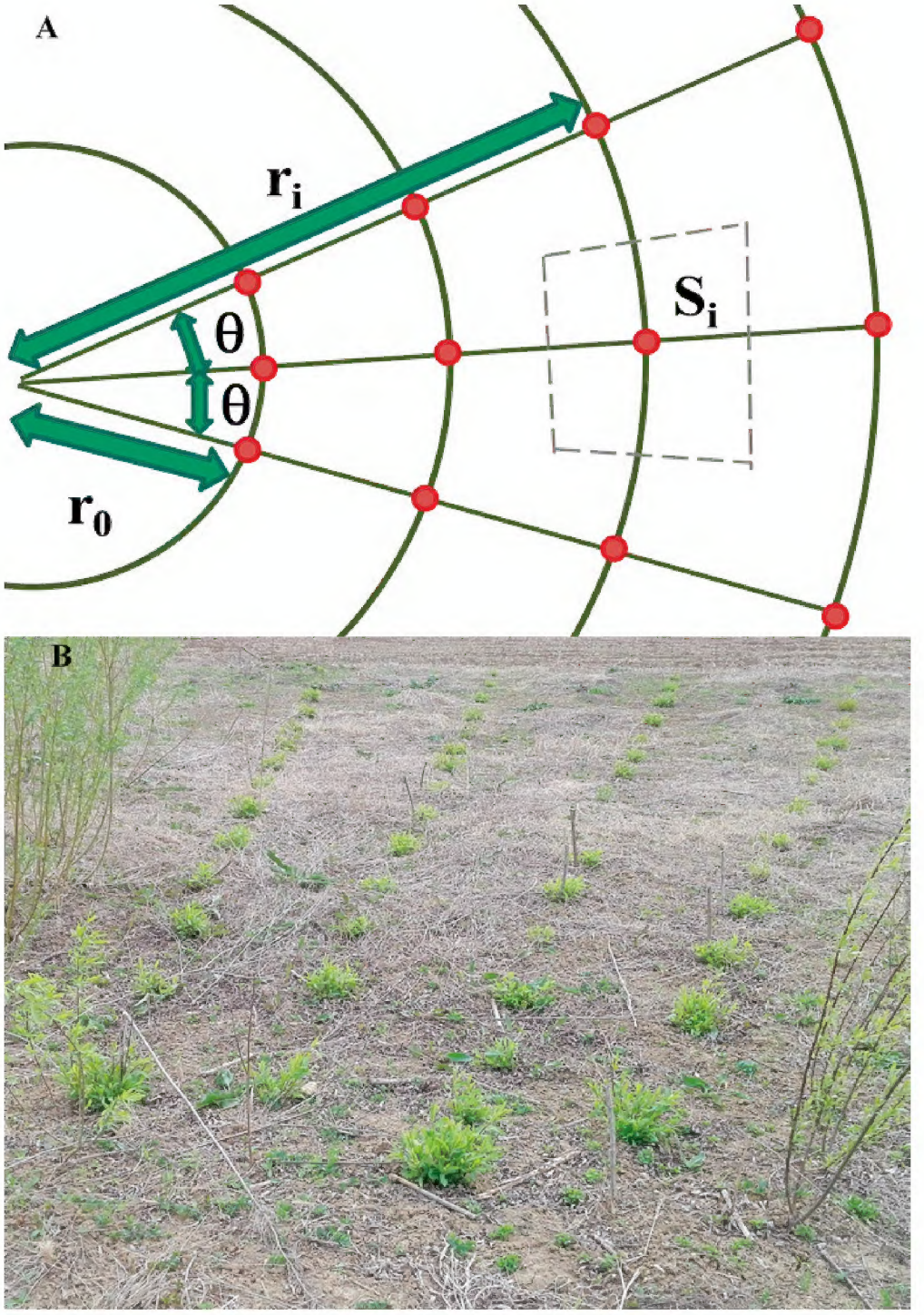

Figure 1. A sector of a Nelder wheel (design Ia). A. Plot parameters; B. Field trial (picture by V. Gyuleva)
Abbreviations: θ – angle between the adjacent spokes, r_0 – radius of the innermost circle, r_i – radius of the i-th circle, S_i – growing space corresponding to the i-th circle

density (Lemoine, 1980; Hummel, 2000; Ferrere et al., 2005; Waghorn et al., 2007; Newton et al., 2012; Kuehne et al., 2013). A tendency to adapt the Nelder wheel experiments to the needs of the short-rotation biomass crops has been manifested in a set of studies where the optimal spacing for maximum yield is studied according to species/genotype, site, age and harvesting cycle (Armstrong et al., 1999; Geyer, 2006; Stankova et al., 2019b, c). Some works have shown that the Nelder design is relevant also to studies of biomass productivity of the lower vegetation layer (Otsamo, 2002) and of complex agroforestry systems of several plant species (Luna et al., 2011a, b, 2012). Other research emphasise the advantages of the design to treat and present growing space as a continuous variable and studied the effect of

spacing on allometry, space-use efficiency, specific competition between contrasting tree species (Vanclay at al., 2013; Uhl et al., 2015). In addition, basic differences in crown architecture and yield physiology among genotypes have been quantified (Hall, 1994) and the validity of the elastic similarity model using scaling with diameter was tested (Waghorn, Watt, 2013). Finally, data from Nelder wheel experiments are applied in elaboration of individual-tree growth and mortality models (Knowe, Hibbs, 1996; Mabvurira, Miina, 2002).

Clones and hybrids of eucalypts and poplars are often explored using Nelder wheels. Results from Nelder spacing trials have been reported also for *Pseudotsuga menziesii* var. *menziesii* (Mirb.) Franco, *Pinus radiata* D. Don, *Pinus brutia* Ten., *Pinus pinaster* Aiton, *Fraxinus excelsior* L., *Alnus rubra* Bong., *Robinia pseudoacacia* L., *Quercus sp*., mixed plantings of *Picea glauca* Moench. Voss. with *Alnus crispa* (Ait.) Pursh. and *Araucaria cunninghamii* Aiton ex D. Don with *Flindersia brayleyana* F. Muell., and other species.

Methodological approaches for data analyses

The usual approach to analyse the data from Nelder spacing trials, particularly at the initial stages of its application and limited to the density factor alone, has been the graphical analysis. Charts presenting the behaviour of the studied tree attributes according to the growing space have been drawn by growth stages, and the observations on the trends and on the absolute values of the parameters of interest have been commented (Delwaulle, 1979; Mark, 1983; Reukema, Smith, 1987). Regression lines or curves are further approximated to the observed trajectories to explore the form and strength of the dependence on the stocking rate (Lemoine, 1980; Giordano, Hibbs, 1993; Imada et al., 1997; Otsamo, 2002; Kerr, 2003; Erkan, Aydin, 2016) and other factors, such as rectangularity and site (Newton et al., 2012). The linear or non-linear regression models have been extended also to more explicit and sophisticated analytical forms, allowing investigation of the presence and nature of spatial correlation between adjacent circumferences by modelling the error structure (Newton, 2015). Similarly, Aphalo and Rikala (2006) apply generalised least squares estimation with the error variance modelled as a function of a covariate logarithm of plant density. Special attention to the presumable significant correlations among neighbouring variable values in a compactly arranged Nelder wheel and their effect on the validity of the classical analysis methods, based on random sampling models and ordinary least squares estimators, is paid in the thesis of Affleck (2001). Affleck (2001) concludes that the estimates of the treatment effects are inefficient and those of the variance parameters are biased in such situations and suggests alternative analysis methods based on spatial correlated error models to be used. Uhl et al. (2015), on the other hand, emphasise on the two principal forms of interaction between the trees: facilitation and competition. In order to better capture the result of these interactions on the tree growth in a Nelder wheel and according to spacing,

they have employed general additive regression models (GAM). Such models provide a way to combine explanatory variables with linear and non-linear influence on a goal variable inside the same model (Uhl et al., 2015). As the relations of interest could not have been assumed to be linear a priori, the non-linear relationships have been modelled as non-parametric smoothing functions. Similar to Vanclay et al. (2013), Uhl et al. (2015) have used the Hegyi's index to evaluate the competition and have included it as a predictor in their model. The GAM method is used also by Kuehne et al. (2013) to analyse the correlation between tree growth and quality parameters as response variables and initial growing space as the main predictor variable.

Some authors emphasized that due to the systematic nature and the experimental unit of the design, regression analysis and not analysis of variance must be applied to the Nelder plots (Mark, 1983; Parrott et al., 2011). Despite this, analysis of variance (ANOVA) and the related post-hoc comparison tests seem to be the form of statistical processing most often used with Nelder wheel data. Most of the researchers find similarity between the structure of the Nelder wheel and that of familiar randomised factorial designs and adopt the respective ANOVA table to the data from their Nelder plots. One-way ANOVA is usually applied when the density effect alone for a species or genotype at a particular age is tested (Ferrere et al., 2005; Erkan, Aydin, 2016). On the other hand, ANOVA for randomised complete block design is used in most of the cases when species or genotype effect is tested together with spacing. A Nelder plot (Krinard, 1985; Waghorn et al., 2007; Kirongo et al., 2012) or a sector within the plot (Panetsos, 1980; Waghorn, Watt, 2013) is regarded as a replication (block) in such situations. Alternatively, ANOVA for split-plot design is applied in some cases, where "species mixture" is regarded as the main plot factor and "spacing" is viewed as the sub-plot effect (Wurtz, 1995; Doran et al., 2001). Grouping of the studied tree variables, according to the different stocking levels included in the Nelder plots, has been extensively explored employing various multiple comparison tests. Starting with the traditional Least Square Difference (LSD) test (Lemoine, 1980), the effect of density on the tree attributes has been categorised also with Duncan multiple range test (Decourt, Lemoine, 1974; Krinard, 1985; Doran et al., 2001), Bonferroni test (Imada et al., 1997), Tukey test (Luna et al., 2011a,b, 2012) and Student-Neuman-Keuls (SNK) test (Waghorn et al., 2007).

Finally, the response surface methodology has also been applied to obtain optimal response of variables of interest for a number of explanatory variables, such as spacing and age (Luna et al., 2011a,b, 2012; Matos et al., 2015).

Pros and cons of the design

Nelder (1962) points out the weaknesses of the full factorial spacing trials, which have motivated the introduction of the circular experimental design. In the classical rectangular plots, because of the density variation, one can keep either the plot

size or the plant number per plot constant. If a constant number of plants per plot is kept, then all the plots are of different sizes and awkward to fit together in a block. In case all plots are of the same size, the close spacings may have an unnecessarily large number of plants in them. Where plant material or land is valuable, these layouts do not provide adequate solutions. Since a range of densities (design 'Ia') or shapes (design 'Ib') is presented even along a single spoke, the Nelder wheel is efficient because of the small total size of the plot area, allowing also homogeneity of the site conditions to be provided.

One important drawback of the Nelder wheel design is the sensitivity of the analysis to tree mortality. Indeed, the loss of even a single plant in the plot changes both size and shape of the growing area of all neighbouring plants. Therefore, it is recommended that seedling survival should be a primary concern when establishing Nelder plantings. Double plantings, intensive weed control, other tending methods, such as fertilisation and immediate replacement of dead plants, where applicable, are considered to increase survival. It has been suggested that trees adjacent to the empty planting spots should be removed from the analysis (Mark, 1983). Another solution in the case of missing plants would be recalculation of the size of the growing space of the surviving neighbours, which consists of allocation of the area of the missing tree equally to each of, at least the four closest, neighbouring trees (Kerr, 2003).

A specificity that can be viewed as both positive and negative feature of the design is its unconventional form and construction. In practical terms, the circular plot form renders difficulties in plantation establishment and tending operations, but the same design, with the same spacings is adaptable also in a rectangular form, if desired (e.g. Ferrere et al., 2005). The unconventional design structure of systematic nature, however, is not bounded by a specific statistical analysis for the cases when spacing is just one of several effect variables, reference of which can be found in the relevant manuals (e.g. Gomez, Gomez, 1984). This lack of explicitly developed statistical approach to Nelder plot data creates a challenge for the scientific community to derive relevant and adequate methods. At the same time, the liberty to adopt methods that are found appropriate, based on personal judgements, carries the risk to produce erroneous results and conclusions. Gayer (2006), for example, speculated that, in a replicated Nelder wheel with three tree species, conclusions from the statistical analysis should be limited only to species differences, because spacings are not randomised. Otsamo (2002), on the other hand, has examined only the effect of spacing and excludes the option to compare the different species, planted in adjacent sectors, although site homogeneity is a prerequisite for a properly established Nelder wheel. A mere comparison of the outcomes of ANOVA for e.g. randomised complete block, split-plot or strip-plot designs, each of which can be found similar to a Nelder wheel, would show completely different results about the presence or lack of significance of the studied factors and their interaction. In addition, if we consider the general recommendation for the design of forest experiments that the quantitative treatments must be analysed quantitatively and not as

separate categories (Binkley, 2008), any ANOVA analysis applied to a Nelder trial carries a principal error regarding "spacing" as a fixed factor instead of a continuous covariate.

Another design peculiarity of ambivalent nature is the particular density values tested in a Nelder wheel. Due to the geometric relationships between the elements of the circle, the growing spaces estimated at the planting points do not exactly coincide with the usual planting schemes, used in the afforestation. This "flaw", however, can as well be viewed as an advantage, if the design is regarded as a close-to-nature experimental layout. Indeed, tree distribution in the forest stands does not follow square or rectangular planting design and the stocking rate can be viewed rather as a continuous variable, which includes a range of values. Therefore, the Nelder wheels present more realistic experimental layouts than the conventional randomised spacing trials.

Nelder design in biomass studies in Bulgaria

Several Nelder wheel trials were established in Bulgaria in 2013-2018 in relation to studies relevant to cultivation of short-rotation plantations for biomass. Two Nelder plots with *Populus* x *euramericana* (Dode) Guinier clones were planted in the spring of 2013, examining 11 planting densities in the range from 870 to 10000 plants per ha (Stankova et al., 2016, 2017). Four clones ('Agathe', 'BL', 'NNDV' and 'I 45/51') in alternating spokes were used in a plantation in North-Western Bulgaria, while two clones ('Agathe' and 'Guardi') were arranged in the same manner in a Nelder plot in South-Western Bulgaria. Two Nelder plots were established in the autumn of 2013: an experimental plantation with two half-sib black locust families in North-Central Bulgaria (Stankova et al., 2018) and a plot with two clones of paulownia in South-Western Bulgaria (Stankova et al., 2019a). The clones and families of the latest were arranged in sectors, with 12 examined densities for the paulownia clones and 16 spacing variants for the black locust families. Finally, a Nelder wheel with three clones of *Salix* was established in North-Central Bulgaria in the spring of 2017 and partially replanted in the spring of 2018. These spacing experiments with fast-growing broadleaves are used in two principal directions, the first of which is of auxiliary nature. The first way to use the experimental plots is for derivation of genotype- and site-specific allometric relationships for estimation of the aboveground biomass from easily measured tree and stand variables, growing space being among the tested predictors (Stankova et al., 2016, 2017, 2018, 2019a). The second direction of study refers to the effect of spacing, genotype, root age and harvesting cycle on the aboveground woody biomass production (Stankova et al., 2019b, c). Two types of statistical analyses were applied to meet the objectives of the second direction of study. First, simple non-linear regression model was employed to derive the optimal planting density for maximum dendromass yield according to genotype and harvesting cycle (Stankova et al., 2019c). Next, the growing space was

considered a continuous variable and was treated as a covariate to the main factor 'parental genotype', 'harvesting cycle' or 'root age'. One-factor analysis of covariance (ANCOVA) was used to examine the influence of the factor and the covariate on the dendromass yield (Stankova et al., 2019b, c). Non-parametric rank transform ANCOVA method proposed by McSweeney and Porter (1971) was employed due to the diagnosed heteroscedasticity of errors. In addition, research on the photosynthetic total chlorophyll content and normalised difference vegetation index (Anev et al., 2018) and on the root systems (Gyuleva et al., 2018) of the poplar clones in the Nelder wheels according to three arbitrarily chosen levels of spacing was also undertaken.

References

Anev, S., S. Damyanova, V. Kotova, A. Stoeva, N. Tzvetkova, V. Gyuleva, T. Stankova. 2018. Total chlorophyll content and normalized difference vegetation index of two *Populus* x *euroamericana* clones ('Agathe' and 'Guardi'). In: Proceeding papers of the International Scientific Conference "90 years Forest Research Institute – for the society and nature", 24-26 October, Sofia: 191-196.

Aphalo, P.J., R. Rikala. 2006. Spacing of silver birch seedlings grown in containers of equal size affects their morphology and its variability. – Tree Physiology, 26, 1227–1237.

Armstrong, A., C. Johns, I. Tubby. 1999. Effects of spacing and cutting cycle on the yield of poplar grown as an energy crop. – Biomass and Bioenergy, 17(4), 305-314.

Binkley, D. 2008. Three key points in the design of forest experiments. – Forest Ecology and Management, 255, 2022–2023.

Decourt, N., M. Lemoine. 1974. Premiers résultats d'une expérience clinale d'espacement avec Populus trichocarpa. – Annales des Sciences Forestières, 31(3), 171-179.

Delwaulle, J.-C. 1979. Plantations forestières en Afrique tropicale sèche. Techniques et Espèces à utilizer. – Revue Bois et Forêts des Tropiques, 184, 45 – 59.

Doran, K., R. W. Ruess, F. G. Plumley, T. L. Wurtz. 2001. Photosynthetic responses of white spruce saplings (*Picea glauca*) to controlled density gradients of spruce and green alder (*Alnus crispa*). – Ecoscience, 8(1), 76-88.

Erkan, N., A.C. Aydin. 2016. Effects of spacing on early growth rate and carbon sequestration in *Pinus brutia* Ten. plantations. – Forest Systems, 25 (2) e064.
http://dx.doi.org/10.5424/fs/2016252-09290.

Ferrere P., G. A. López, R. T. Boca, M. A. Galetti, C. A. Esparrach, P. S. Pathauer. 2005. Efecto de la densidad de plantación sobre el crecimiento de *Eucalyptus globulus* en un ensayo Nelder modificado. – Investigación agraria. Sistemas y recursos forestales, 14(2), 174-184.

Geyer, W. A. 2006. Biomass production in the Central Great Plains USA under various coppice regimes. – Biomass and Bioenergy, 30, 778–783.

Giordano, P. A., D. E. Hibbs. 1993. Morphological response to competition in red alder: the role of water. – Functional Ecology, 7, 462-468.

Gomez, K. A., A. A. Gomez. 1984. Statistical procedures for agricultural research. John Wiley and Sons, Inc. Singapore. Second edition.

Gyuleva, V., M, Zhiyanski, T. Stankova, M. Glushkova, E. Andonova. 2018. Clone differences in the root biometry of hybrid black poplar. In: Proceeding papers of the International Scientific Conference "90 years Forest Research Institute – for the society and nature", 24-26 October, Sofia: 91-105. (in Bulgarian with English summary)

Hall, R. B. 1994. Use of the crown competition factor concept to select clones and spacings for short-rotation woody crops. – Tree physiology, 14(7-8-9), 899-909.

Hummel, S. 2000. Height, diameter and crown dimensions of *Cordia alliodora* associated with tree density. – Forest Ecology and Management, 127, 31-40.

Imada, M., T. Kunisaki, N. Mizoue, Y. Teraoka. 1997. Optimum Planting Density for Japanese Oak (*Quercus mongolica* vat. *grosseserrata*) based on spacing experiment with systematic design. – Journal of Forest Research, 2, 89-93.

Kerr, G. 2003. Effects of spacing on the early growth of planted *Fraxinus excelsior* L. – Canadian Journal of Forest Research, 33, 1196–1207.

Kirongo, B.B., A. S. Mbelase, K. Senelwa, J. Hitimana, L. Etiegni. 2012. Spacing and genotype on height and diameter growth of four eucalyptus under short rotation. – Jurnal Manajemen Hutan Tropika, 18 (1), 1-9.

Knowe, S. A., D. E. Hibbs. 1996. Stand structure and dynamics of young red alder as affected by planting density. – Forest Ecology and Management, 82(1-3), 69-85.

Krinard, R. M. 1985. Cottonwood development through 19 years in a Nelder's design. Res. Note SO-322. New Orleans, LA: US Department of Agriculture, Forest Service, Southern Forest Experiment Station. 4 p., 322.

Kuehne, C., E. Kublin, P. Pyttel, J. Bauhus. 2013. Growth and form of *Quercus robur* and *Fraxinus excelsior* respond distinctly different to initial growing space: results from 24-year-old Nelder experiments. – Journal of Forestry Research, 24(1), 1-14.

Lemoine, B. 1980. Densité de peuplement, concurrence et coopération chez le pin maritime. II. Résultats à 5 et 10 ans d'une plantation à espacement variable. – Annales des Sciences Forestières, 37(3), 217-237

Luna, J. M. E. A., F. J. Solorio-Sánchez, S. Hernández-Daumás, E. Huerta-Lwanga, P. A. Macario-Mendoza. 2011a. Interacciones radicales y aéreas en la asociación agroforestal cedro-limón-chaya. – Tropical and subtropical agroecosystems, 14(2), 441-451.

Luna, J. M. A., P. A. M. Mendoza, S. H. Daumás, E. H. Lwanga, R. de Alba Becerra. 2011b. Crecimiento y productividad en la asociación agroforestal cedro-limón-chaya a diferente densidad de plantación. – Revista Brasileira de Ciências Agrárias, 6(4), 694-702.

Luna, J. M. E. A., E. García-Villanueva, P. A. Macario-Mendoza, E. Huerta-Lwanga, R. de Alba-Becerra. 2012. Effect of the plantation density in the growth and productivity of *Cnidoscolus chayamansa* McVaugh (Euphorbiaceae). – Tropical and Subtropical Agroecosystems, 15(1), 77-86.

McSweeney, M., A.C. Porter. 1971. Small Sample Properties of Nonparametric Index of Response and Rank Analysis of Covariances. Occasional paper no. 16, Office of Research Consultation. Michigan State University.

Mark, W. B. 1983. Spacing trials using the Nelder wheel. In: Standiford R. B., Ledig F. T. (eds) Proceedings of a work-shop on *Eucalyptus* in California. USDA For. Serv., Pacific Southwest Forest and Range Experiment Station, Berkeley, CA, Gen. Tech. Rep., 81-86.

Matos, F. A., O. Daniel, A. Pereira Serra, D. Menani Heid, J. Matos do Nascimento, I. M. Bumbieris Nogueira, S. Cândido Ensinas, P. Henrique Altomar, V. do Amaral Conrad, D. Costa Potrich, M. Andrade Martinez. 2015. Effects of intra-specific tree competition on dendrometric parameters of *Peltophorum dubium*. – Australian Journal of Crop Science, 9(11),1003-1009.

Mabvurira, D., J. Miina. 2002. Individual-tree growth and mortality models for *Eucalyptus grandis* (Hill) Maiden plantations in Zimbabwe. – Forest Ecology and Management, 161(1-3), 231-245.

Namkoong, G. 1965. Application of Nelder's designs in tree improvement research. In: Southern Forest Tree Improvement Committee (ed) Proceedings of the eighth southern conference on forest tree improvement. School of Forestry, North Carolina State College, Raleigh, NC, 24-37.

Nelder, J.A. 1962. New kinds of systematic designs for spacing experiments. – Biometrics 18, 283–307.

Newton, P. F. 2015. Occurrence of Density-Dependent Height Repression within Jack Pine and Black Spruce Populations. – Forests, 6, 2450-2468. doi:10.3390/f6072450.

Newton, M., B. Lachenbruch, J. M. Robbins, E. C. Cole. 2012. Branch diameter and longevity linked to plantation spacing and rectangularity in young Douglas-fir. – Forest Ecology and Management, 266, 75-82.

Otsamo, A. 2002. Early effects of four fast-growing tree species and their planting density on ground vegetation in *Imperata* grasslands. – New Forests, 23, 1–17

Panetsos, K. P. 1980. Selection of new poplar clones under various spacings. – Silvae Genetica, 29 (3-4), 130-135.

Reukema, D. L., J. H. G. Smith. 1987. Development over 25 years of Douglas-fir, western hemlock, and western red cedar planted at various spacings on a very good site in British Columbia. Res. Pap. PNW-RP-381. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 46 p.

Stankova, T., H. Hristova, E. Popov, I. Tsvetkov. 2016. Clone-specific biometric models for aboveground dendromass of single-stem and coppiced black poplar clones differing in age and spacing. – Forestry Ideas, 22 (2), 153-170.

Stankova, T., V. Gyuleva, E. Popov, D. N. Dimitrov, E. Andonova. 2017. Stump-level allometric models for aboveground dendromass of two coppiced black poplar clones in south-western Bulgaria. – Silva Balcanica, 18(2), 15-28.

Stankova, T., V. Gyuleva, K. Kalmukov, D. N. Dimitrov, E. Popov, M. Glushkova, P. Dimitrova, H. Hristova. 2018. Woody biomass estimation of coppiced plants from open pollinated progenies of two selected black locust clones. In: Proceeding papers of the International Scientific Conference "90 years Forest Research Institute – for the society and nature", 24-26 October, Sofia: 251-266.

Stankova, T., V. Gyuleva, D. N. Dimitrov, E. Popov. 2019a. Allometric relationships for estimation of aboveground woody biomass of two clones paulownia at juvenile age. – Nauka za gorata, 55(2), 43-54

Stankova, T., V. Gyuleva, E. Popov, K. Petkova, D. N. Dimitrov, V. Biserkov, E. Andonova, P. Stefanova. 2019b. Impact of spacing, clone and coppicing on biomass production of two black poplar hybrids. – Forestry Ideas, 25(2), 351-368

Stankova, T., V. Gyuleva, K. Kalmukov, E. Popov, C. Pérez-Cruzado, M. Glushkova, D. N. Dimitrov, P. Dimitrova, H. Hristova, E. Andonova. 2019c. Effect of spacing, parental genotype and harvesting cycle on biomass production in two half-sib progenies of *Robinia pseudoacacia* L. – Forestry: An International Journal of Forest Research, https://doi.org/10.1093/forestry/cpz039

Uhl, E., P. Biber, M. Ulbricht, M. Heym, T. Horváth, F. Lakatos, J. Gál, L. Steinacker, G. Tonon, M. Ventura, H. Pretzsch. 2015. Analysing the effect of stand density and site conditions on structure and growth of oak species using Nelder trials along an environmental gradient: experimental design, evaluation methods, and results. – Forest Ecosystems. DOI 10.1186/s40663-015-0041-8

Vanclay, J. K., D. Lamb, P. D. Erskine, D. M. Cameron. 2013. Spatially-explicit competition in a mixed planting of *Araucaria cunninghamii* and *Flindersia brayleyana*. – Annals of Forest Science, 70(6), 611-619. DOI: 10.1007/s13595-013-0304-x.

Waghorn, M. J., M. S. Watt. 2013. Stand variation in *Pinus radiata* and its relationship with allometric scaling and critical buckling height. – Annals of Botany, 111, 675–680. doi:10.1093/aob/mct015

Waghorn, M. J., E. G. Mason, M. S. Watt. 2007. Assessing interactions between initial stand stocking and genotype on growth and form of 17 year old *Pinus radiata* in Canterbury. – New Zealand Journal of Forestry, 52(1), 24.

Wurtz, T. L. 1995. An efficient design for studies of plant species interactions: an example with white spruce and alder. Special Publication – Agronomy Society of New Zealand, 51-58.